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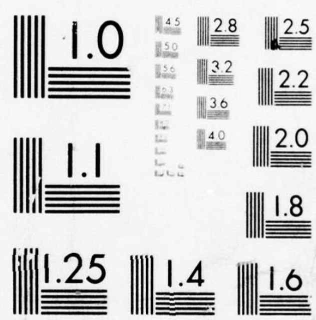

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A.R. MAHONEY

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Experimental facilities and preliminary results, obtained as part of the W.R.E. contribution to a task on the utilization of wind-structure data in aircraft operations, are outlined.

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1. INTRODUCTION

Large and unexpected variations in the low-level wind field (wind shears) can create potentially hazardous situations for aircraft during take-off and, in particular, during the approach and landing. Such wind shears are often associated with atmospheric turbulence (gusts), stably-stratified temperature inversions, weather 'fronts' and with the 'gust fronts' generated by thunderstorms. In general, the facilities for wind measurements at airports do not provide adequate information for operational use on the spatial and temporal distribution of potentially hazardous wind shears, and particularly on transient phenomena such as 'gust fronts'.

Because of the importance of wind-structure measurements for operational use by pilots and air-traffic controllers, and the recognition that wind shear has been a major factor in a number of accidents involving commercial and military aircraft, considerable effort is now being devoted (particularly in the United States) to the development of suitable wind sensors and wind-shear warning and display systems(ref.1). A number of acoustic and electromagnetic remote-sensing systems are currently being investigated, together with passive sensors (e.g. pressure transducers) and airborne systems which indicate, for example, the difference in wind velocity between the ground and the height of the aircraft. Acoustic remote wind-sensing systems(refs.2,3) are in an advanced stage of development, but the maximum height to which wind data may be measured and the reliability of these data can be severely limited in the vicinity of airports by high ambient noise levels created by aircraft and meteorological factors such as rain, strong winds, etc. Remote sensors employing lidars(ref.4) and FM-CW electromagnetic radars(ref.5), currently being developed, show considerable potential for airport wind measurements. These latter systems may have the advantage of all-weather operation, and may be able to provide wind information to ranges of several kilometres along the glide path.

The current Air 74/14 task, which is outlined in the following sections, was initiated by Air Office and was stimulated by a report on the acoustic remote-sensing experiment conducted at Stapleton International Airport(ref.2) from October, 1973 to March, 1974. Subsequent meetings and discussions resulted in the formulation of a task involving the measurement of wind structure around military airfields and the presentation of these wind data in near real time to pilots and air-traffic controllers. Because both measurement and presentation aspects were involved, a joint task involving personnel and facilities in the Aeronautical Research Laboratories (expertise in aircraft modelling, data presentation, etc.) and the Weapons Research Establishment (expertise in remote acoustic wind sensing), was necessary to satisfy the required programme of research. Brief details of the objectives of the task and the sub-studies to be conducted, are outlined in Section 2.

This technical report describes the facilities developed at the Weapons Research Establishment, and the experimental results obtained during the first twelve months of the Air 74/14 task. Acoustic sounding techniques are reviewed briefly in Section 3, followed in Section 4 by a description of the acoustic wind-sensing facility at Edinburgh R.A.A.F. airfield. The experimental data presented in Section 5 are restricted primarily to an outline of the performance of the acoustic wind sensing system, and problems which have either been overcome, or will require further investigation. A brief description of the mobile acoustic wind-sensing system currently being developed is given in Section 6, and further research to be conducted as necessary to improve the performance of acoustic remote-sensing systems is considered in Section 7. Subsequent reports will be devoted to a more detailed description of the electronics subsystems and to statistical data on wind structure at the Edinburgh airfield.

2. BRIEF SUMMARY OF THE TASK

The objectives of the Air 74/14 task are to investigate the scientific and technical feasibility of a wind structure sensing system capable of measuring wind structure in the vicinity of airfields and presenting this information in an acceptable form, and in near real time, to the users. The required accuracy, timeliness of, and appropriate procedures for using such wind information, is to be determined, along with appropriate methods of data presentation. The time scale is two years, with results and recommendations due late in 1977. A programme review is to be carried out early in 1977 and the need for a Phase 2 programme will be considered at this milestone.

The responsibility for overall coordination between the Aeronautical Research Laboratories (A.R.L.) in Melbourne and the Weapons Research Establishment has been assigned to A.R.L.

The sub-studies to be conducted by A.R.L. include (a) field examination of the current system and problems, (b) assessment of the responses of typical fixed-wing aircraft to representative wind patterns, and (c) identification of significant variables. The W.R.E. sub-studies which are considered in the following sections, are:

(i) Assessment of acoustic wind sensor performance

Measurements are to be conducted at Edinburgh airfield to determine the optimum acoustic wind-sensing configuration and to obtain adequate statistical wind data.

(ii) Assessment of wind sensors

An assessment is to be made of the performance of various methods for the sensing of wind structure in the lower atmosphere.

(iii) Investigation of wind structure

Measurements are to be conducted to determine temporal and spatial variations of wind structure over an airfield.

The acoustic wind-sensing facility established at the Edinburgh airfield to satisfy sub-study (i) above is described in Section 4. The assessment of other forms of wind sensors (ii) is outlined briefly in Section 7, and the mobile acoustic wind-sensing facility developed to assist in sub-study (iii) is considered in Section 6.

3. ACOUSTIC SOUNDING TECHNIQUES

The acoustic sounder(refs.2,3) is a ground-based remote sensing technique which exploits the relatively strong interaction between acoustic waves and small scale inhomogeneities of air temperature and velocity, created within turbulent regions of the lower atmosphere. In practice, short pulses of acoustic waves are transmitted upwards into the atmosphere at intervals of typically, two to ten seconds, using a highly directional acoustic antenna on the ground. As the pulses travel through turbulent regions, a small fraction of their energy is scattered back towards the ground. Some of this scattered energy is subsequently collected by one or more acoustic antennas, amplified, and recorded to give information on the height and intensity of scattering regions in the lower atmosphere as a function of time of day. The maximum operating height range is determined by factors such as the availability of scattering inhomogeneities, the atmospheric absorption of the energy of the transmitted pulses and the ambient noise level, which determines the minimum detectable signal level. Typical operating height ranges for low-powered (about 10 to 50 W peak radiated acoustic power) acoustic sounders operating in the frequency range 1000 to 3000 Hz, would vary from about 100 m to one kilometre, depending upon the antenna configuration employed and the ambient noise levels.

When the small scale air temperature and velocity inhomogeneities are moving relative to a fixed receiving antenna on the ground, the frequency of the scattered acoustic waves, as observed at the receiver, differs from the carrier frequency of the transmitted pulses. The magnitude of these Doppler frequency shifts depends primarily upon the wind velocity at the heights of the scattering regions and the particular acoustic sounder configuration employed. For example, when small scale inhomogeneities of air temperature are available to act as tracers or natural targets, a monostatic configuration (co-located transmitting and receiving antennas) can be employed to measure the 'radial' component of the three dimensional wind field along the path travelled by the transmitted pulses. Alternatively, Doppler wind information can be obtained over a limited height interval using a bistatic configuration (spaced transmitting and receiving antennas) when small scale inhomogeneities of air temperature and/or velocity are available to scatter some of the transmitted acoustic energy back to a collecting antenna on the ground. In general a minimum of three antennas is necessary, using either monostatic or bistatic techniques to obtain information on the three-dimensional wind field.

The distinction between monostatic and bistatic operation is particularly important for acoustic-sounding applications because of the nature of the scattering processes for acoustic waves in the lower atmosphere. Theoretical investigations (ref.6) predict that, if temperature inhomogeneities are absent, scattered acoustic energy can be received from air velocity inhomogeneities using a bistatic configuration, but not when using a monostatic configuration. This would suggest that the (generally more complicated) bistatic antenna configuration would be necessary to maintain reliable wind measurements using acoustic remote-sensing techniques. The antenna configurations employed to measure wind information and to investigate the performance and reliability of monostatic and bistatic systems are described in Section 4.

4. THE EDINBURGH ACOUSTIC WIND-SENSING FACILITY

A diagram illustrating the main features of the acoustic wind-sensing facility at Edinburgh airfield is shown in figure 1. Five parabolic antennas of diameter 2 m, are arranged in a configuration which allows both monostatic and bistatic wind-sensing techniques to be compared simultaneously. Four antennas, located 90 m from the centre along the north, south, east and west axes, are inclined at angles of 60° to the horizontal and are directed towards a common scattering

region 160 m above the vertically pointing antenna at the centre. Shielded cables are employed to connect the antennas to a fixed van containing the transmitting, receiving and recording electronics. Wind speed and direction at a height of ten metres are measured using a cup anemometer and a wind vane on a nearby tower. The photograph (figure 3) shows the van, 10 m tower and the west acoustic antenna (white, on the left). The smaller (0.6 m diameter) antenna shown near the van was employed near the south antenna to investigate the effect of increased receiving antenna beamwidth on bistatic returns (see Section 5).

The basic monostatic and bistatic antenna configurations available for the measurement of wind information at the Edinburgh site are shown in figure 2. Vertical (monostatic) velocity can be obtained by measuring Doppler frequency shifts on the centre antenna, which is surrounded by a wooden screen lined with glass wool to reduce the received level of ambient noise (figure 2(a)). The radial component of the wind velocity at an angle of 30^{o} to the vertical can be measured along the north-south and east-west axes using the inclined monostatic configuration shown in figure 2(b). In the bistatic configuration illustrated in figure 2(c), pulses of acoustic waves are transmitted vertically using the centre antenna and (bistatic) scattered energy is collected from a common scattering volume using the inclined acoustic antennas. Bistatic Doppler information from the common scattering volume can also be obtained, by receiving on the centre antenna when any of the inclined antennas transmit. Up to eight monostatic and/or bistatic modes of operation can be selected using a digital control panel in the fixed van (see figure 5).

During the period from November, 1975 to July, 1976 a 'multimode' sequence (repeated every eight seconds) was employed to compare monostatic and bistatic wind data. Pulses were transmitted at two second intervals in the sequence, centre antenna (to give vertical monostatic and north,south,east and west bistatic Doppler information), south antenna (north-south monostatic Doppler), centre antenna (as above) and west antenna (east-west monostatic Doppler). Wooden screens were added to the north and east antennas, to reduce ambient noise levels,in July, 1976 and monostatic transmissions subsequently transferred from the south and west to these screened antennas. The bistatic configuration was varied in January, 1977 to collect bistatic data on the centre antenna, as outlined in Section 7. Information derived from the 'multimode' configuration and the various experiments conducted since November, 1975 are outlined in Section 5.

A simplified block diagram of the transmitting, receiving and recording system in the fixed van at the Edinburgh site is shown in figure 7. The transmit/receive sequences on the various acoustic antennas are controlled by a programmable, 'timing and digital mode-control unit', described below. In the transmit mode, short pulses of acoustic energy at a frequency of 2500 Hz are transmitted by switching the respective antennas to 100 W audio power amplifiers for a duration which can be selected from the range, 50, 100 or 150 ms. The rise and fall times of the transmitted signal pulse are controlled, to reduce the possibility of damage to the acoustic transducers caused by voltage transients.

In the receive mode, the weak electrical signals, produced when scattered acoustic energy is collected by the antenna systems, are amplified by pre-amplifiers and passed through bandpass filters to reduce unwanted noise. Amplitude and Doppler receivers are subsequently employed to produce respectively, a height versus time record of atmospheric 'microstructure' on a facsimile recorder, and Doppler frequency shifts resulting from the motion of the scattering inhomogeneities relative to the fixed receiving antennas. The large variation in intensity of the scattered returns, which occurs with different meteorological conditions, is reduced for recording purposes by using logarithmic amplifiers with a large dynamic operating range.

Doppler, amplitude and surface meteorological data are sampled by a 32 channel analogue multiplexer and averaged over intervals of two minutes using a micro-computer. Tracking-loop ('lock indicator') voltages from the Doppler receivers are also monitored to ensure that the microcomputer accepts only good quality Doppler data for averaging (signal-to-noise ratio greater than unity). The averaged wind data from twenty height intervals (range gates) in the lower 300 m are plotted on X-Y recorder (selected data for monitoring purposes), and punched on paper tape for subsequent transfer to magnetic tape and processing on the W.R.E. computer. System timing and the selection of the required transmit/receive mode of operation are controlled by the 'timing and digital mode control' unit.

The majority of electronic equipment in the fixed van is shown in figure 4. The racks, numbered 1 to 5 from the left of the photograph, contain (1) 100 W transmitters, (2) preamplifiers, bandpass filters, Doppler and amplitude receivers, etc., (3) 32 channel analogue multiplexer, microcomputer and digital mode control unit, (4) facsimile recorder for recording the intensity of scattered returns on selected antennas as a function of time-of-day and (5) X-Y plotter with incremental chart advance for monitoring selected channels of averaged wind data. A photograph of the microcomputer and digital timing and mode control unit is shown in figure 5. The microcomputer, built on a single card, contains an Intel 8008 CPU, 2048 bytes of programmable read-only memory (PROM), 1024 bytes of random access memory (RAM), and timing and interface circuitry. The processing of data following a given 'transmit' pulse is initiated using the external 'interrupt' facility shown on the left. Switch and status registers in the timing and mode control unit (indicating the current antenna transmitting, the pulse duration and repetition period, and the operating mode) are then examined and the appropriate data from the 32 channel multiplexer are averaged and stored in memory (RAM). Plotting and paper-tape punching sequences are initiated following an averaging period of approximately two minutes.

The 'timing and mode control' unit, shown at the top of figure 5, contains an eight-bit 'switch' register (switches on the front panel), transmit pulse duration switch (50, 100 or 150 ms), a display of time in hours and minutes (also punched on paper tape) and five lights (marked N, S, E and W in the figure) to indicate which antenna is transmitting. The three switch register 'bits' on the right, marked 'PROGRAMME', allow the selection of up to eight modes of operation (transmit/receive sequences) programmed into a read-only memory (PROM). The next pair of switches to the left control the pulse repetition period, which can be set to two, four or eight seconds. Monostatic transmissions can be transferred from the north to south and east to west antennas, as required, by means of a further pair of switches. The unit also contains digital-to-analogue converters and low-pass filters for the X-Y recorder output, and circuitry to interface the microcomputer with the analogue multiplexer and paper-tape punch. Various functions, such as the availability of new data, the current antenna transmitting and paper-tape operation, are monitored by the microcomputer using 'bits' in a 'status register' provided by the unit.

5. EXPERIMENTAL DATA FROM THE EDINBURGH FACILITY

5.1 General

The experimental data presented in the following sections are concerned primarily with the performance of the monostatic and bistatic configurations employed at the Edinburgh facility, and with problems relevant to the operation of acoustic wind-sensing systems. The characteristics of the received acoustic signals are considered in Section 5.2, followed by statistical data on monostatic and bistatic system performance in Section 5.3. The reliability of computed monostatic wind data is considered briefly in Section 5.4. Additional problems encountered, which are discussed in Section 5.5, include the influence of antenna sidelobes on bistatic wind measurements, and the effects of ambient noise and mains harmonics on the outputs of Doppler tracking loops.

5.2 Characteristics of the received signals

Examples of the signals received using monostatic and bistatic configurations, and the outputs of the Doppler tracking loops are shown in figure 8. The envelope of a typical monostatic return, plotted as a function of time in seconds (proportional to height above the ground) after the transmission of a pulse is shown in figure 8(a). This record illustrates the effect of atmospheric absorption and spherical divergence of the scattered acoustic wave on the magnitude of the received echoes. Backscattered returns are strong near the ground and decrease in amplitude with increasing height towards the ambient noise level, which determines the signal-to-noise ratio and therefore, the maximum operating range. The envelope is also shown to have a low frequency, 'burst-like' characteristic (not adequately understood) which causes variations in the signal-to-noise ratio.

Figures 8(b) and 8(c) respectively show typical monostatic and bistatic Doppler 'beats', derived by removing the transmitted carrier frequency, and corresponding output voltages from a particular Doppler 'tracking loop'. The characteristics of the analogue tracking loop are such that a d.c. voltage proportional to the Doppler frequency shift is produced when the signal-to-noise ratio is adequate for the loop to 'acquire' and 'track' a given signal (the loop is then said to be 'in lock'). At low signal-to-noise ratios, the loop may not be able to acquire or track a signal (loss of 'lock') and large, random variations in output voltage can result. The use of some form of 'lock indicator' is therefore necessary to distinguish between 'good' and 'bad' Doppler data. These effects are illustrated in figures 8(b) and 8(c).

In figure 8(b), strong monostatic returns, characterized by a well-defined Doppler frequency, are shown from the region near the ground. The relatively constant output voltage from the Doppler tracking loop (indicating a Doppler frequency shift of about -50 Hz from the 2500 Hz carrier) indicates that the loop has acquired and is 'tracking' the backscattered signal. Note, however, that nulls in the envelope to the scattered returns can cause a temporary loss of lock and possible errors in the measured Doppler information. The signal-to-noise ratio from higher levels is poor, and large excursions in tracking-loop output can be seen. Wind data from this region would have to be considered 'poor' and eliminated from the data averaging system. In figure 8(c), the signal-to-noise ratio for bistatic returns from the common scattering volume is shown to be adequate for the loop to acquire and track the received signal. Because of the scattering geometry, the frequency of the bistatic Doppler 'beats' is generally lower than would be obtained with a monostatic system directed towards the scattering volume. Poor signal-to-noise ratios above and below the scattering volume are characterized by a loss of lock and large output-voltage excursions, which would again have to be eliminated from the averaging system.

5.3 Statistical data on monostatic and bistatic system performance

Statistical data for time intervals 0000 to 0600, 0600 to 1200, 1200 to 1800 and 1800 to 2400 C.S.T. (local time) on the performance of the monostatic and bistatic systems employed at the Edinburgh facility are given in figures 9 and 10 respectively. In the case of statistical data based on a short observation period, for a system with many variables, care must be taken in interpreting the results as giving an accurate representation of the performance. For this reason, figure 9 and 10 should be interpreted as giving an approximate performance estimate appropriate to the type of low powered (10 to 30 W peak radiated acoustic power) acoustic wind sensing system employed at Edinburgh. Experimental results for other configurations less susceptible to high levels of ambient noise and meteorological factors will be presented in the final report.

In figure 9, the percentage of time that good quality monostatic Doppler data was recorded over a period of about one month is plotted as a function of height in metres for the vertically pointing centre screened antenna (solid line), an inclined, screened antenna (heavy dotted line) and an unscreened, inclined antenna. The Doppler data recorded from a given height were assumed to be 'good' when the respective Doppler tracking loops were 'in lock' for greater than half the number of samples available for averaging over a two minute period (64 samples for the centre and 32 for the two inclined antennas).

The maximum useful monostatic wind data, to the greatest height, were recorded during the early morning period from 0000 to 0600 C.S.T., as shown in figure 9(a). This period is frequently characterized by low ambient noise levels (light winds and reduced aircraft and traffic noise) and the availability of scattering (temperature) inhomogeneities generated within stably-stratified temperature inversions. The maximum operating height for both screened and unscreened monostatic systems which yielded 75% useful data was in excess of 200 m. The performance of the monostatic systems, particularly the unscreened antenna, is shown to deteriorate during the day (figures 9(b) and (c)). This daytime period generally coincides with increased ambient noise levels (aircraft, traffic, stronger winds and turbulence) and with near adiabatic conditions at upper height levels, characterized by a significant reduction in the availability of suitable scattering (temperature) inhomogeneities. Typical operating heights for 75% useful monostatic data during the day varied from as low as about 100 m for the unscreened, inclined antenna, to about 200 m for the screened vertically pointing antenna. For all periods, the performance of the latter antenna was superior to that of the inclined antennas which, (because of 'sidelobe' distribution) generally have less discrimination against ambient noise.

The percentage of time that useful bistatic wind data was recorded, over a period of about one month, is plotted as a function of height for the same six-hour periods in figure 10. The three curves represent data for 2 m diameter receiving antennas with wooden screens lined with glass wool (solid lines), unscreened and on the surface (heavy dotted lines), and in a shallow hole (for a period of about one week), respectively. The additional (dash-dot) curve in figure 10(c) represents data measured during the 1200 to 1800 period using a 0.6 m diameter receiving antenna set in a shallow hole (see figure 3). These results illustrate firstly, that the strongest returns are obtained from the vicinity of the common scattering volume (as shown in figure 2(c)) and secondly, that the use of screening pits or acoustic screens is desirable to maintain consistent performance over a 24 hour period.

Because of the limited vertical extent of the common scattering volume, determined by the narrow beamwidth (about 5°) of the 2 m diameter receiving antennas, an alternative system would be required to obtain reliable bistatic wind information from a large height interval. Possible solutions would involve:

(a) increasing the beamwidth of the receiving antenna to accept scattered acoustic energy from a greater height range.

(b) using a number of directional antennas with receiving beams directed to cover the required height range, or

(c) electronically steering the receiving beam to track the returns from the pulse propagating upward from the centre antenna.

The results in figure 10(c), obtained using a 0.6 m diameter receiving antenna (beamwidth about 16°), indicate that useful wind data can be obtained over a larger height interval by increasing antenna beamwidth. However, the maximum percentage of useful data was found to be reduced due to a reduction in the collecting area for scattered acoustic energy, accompanied by less discrimination against ambient noise. Problems associated with antenna sidelobes can also cause errors in measured bistatic Doppler wind data when large beamwidths are employed, as outlined in Section 5.5. Disadvantages of methods (b) and (c) above are increased complexity (a minimum of three such antenna systems would be required for bistatic wind measurements), and a probable increase in the collection of ambient noise power, for receiving antenna beams directed at small angles above the horizontal.

The development of an alternative bistatic configuration with a common, vertically pointing receiving antenna, and inclined transmitting antennas directed towards a common scattering volume, has been described in the literature(ref.3) and is currently being investigated at the Edinburgh facility. Although several inclined transmitting antenna systems are required, the common receiving antenna at the centre can be screened from ambient noise relatively easily. The performance of this new bistatic configuration, which will be detailed in the final report, should be superior to that of the single transmitting antenna and multi-antenna receiving system previously employed at Edinburgh.

An essential requirement for any remote wind-sensing system is the ability to operate under all conditions likely to be associated with wind-shear phenomena, including strong surface winds and turbulence, gusts, etc. The statistical data in figures 9 and 10, on the performance of the monostatic and bistatic systems employed at Edinburgh would not be complete, therefore, without a brief consideration of the factors contributing to poor signal-to-noise ratios and a subsequent loss of useful Doppler wind data. The loss of data above and below the common scattering volume for bistatic data, in figure 10, will be attributed to the characteristics of the antenna radiation patterns and not considered further.

In general, heavy rain and aircraft on the nearby runway (see figure 1) cause a total loss of useful monostatic and bistatic (common volume) wind data. The other major factors contributing to poor performance, particularly with the monostatic system, are the absence of adequate (temperature) scattering inhomogeneities and high ambient noise levels generated by strong surface winds. The use of improved acoustic screening, higher transmitted powers and more sophisticated signal and data processing techniques will be necessary to improve the performance of acoustic wind-sensing systems during such periods.

An indication of the relationship between surface wind speed and the performance of the antenna configurations employed at the Edinburgh facility is given in figure 11 for four, six-hour periods. These data, which were recorded from a height of approximately 160 m over a period of about one month, represent the percentage of samples for which the surface wind speed exceeded a given value (in m/s) with the respective tracking loops 'out of lock' over the recording period. Although other sources of noise are included, figure 11 should give a reasonable indication of the effect of surface wind speed on acoustic sensor performance, and the probability that 'poor' wind data will be recorded with the type of acoustic sensor employed at Edinburgh. The curves for the unscreened, 2 m diameter bistatic antenna (solid line) show a strong dependence upon surface wind speed, particularly during the 0600 to 1800 period. In this period about 75% of wind data from 160 m could be expected to be 'poor' for surface speeds in excess of about 8 m/s, rising to about 90% 'poor' for speeds in excess of 10 m/s. The performance of the screened, 2 m diameter monostatic system (heavy dotted line) is also shown to be degraded with increasing surface wind speed, particularly during the 1200 to 2400 period, when adequate backscattering inhomogeneities may not be available, or ambient noise due to other sources may be high. For all time intervals, the screened, 2 m diameter bistatic system (lightly dotted lines) is shown to be less susceptible to increasing surface wind speed.

The dependence upon surface wind speed shown in figure 11 occurs mainly because strong winds and turbulence increase the ambient noise level, which subsequently reduces the signal-to-noise ratio for scattered returns from a given height. Eventually the signal-to-noise ratio is reduced to such an extent that the Doppler tracking loops are unable to provide useful wind data. This surface-wind dependence can be reduced by increasing the magnitude of the scattered signal using high powered transmitters, by reducing the effect of ambient noise power through improved screening, or by reducing the effective noise bandwidth through advanced signal-processing techniques (spectral analysis, pulse compression, etc.).

5.4 Statistical wind data

Statistical data on the wind field measured at Edinburgh airfield will be considered in the final report, following the completion of the task. However, some statistical monostatic wind data, collected over a period of about one month are presented in figure 12, for six-hour intervals. These illustrate the effect (described in the preceding section) of high ambient noise levels associated with strong surface winds on the computed wind distribution. The curves are for monostatic data and indicate the percentage of time (over one month) that the measured wind speed at a given height exceeded values of 4 m/s and 8 m/s respctively, in each of the four time intervals. Corresponding data derived from the surface anemometer are shown as 'dots' at a height of 10 m.

In general, such statistical data could be expected to show an increase in wind speed with height as indicated, for example, by the 4 m/s curves during the 0000to 0600 and 1800 to 2400 periods. While the results for the 0600 to 1200 period could be correct, the 4 m/s and 8 m/s curves show a statistical decrease in wind speed with height during the 1200 to 1800 period. This apparent decrease is probably due to an increase in the number of 'poor' data samples with increasing wind speed, as shown for a height of 160 m in figure 11. Because of atmospheric absorption and spherical divergence of the scattered acoustic energy, the dependence upon surface wind speed and hence, the number of 'poor' data samples will increase above 160 m. Statistical estimates of the wind

speed distribution at higher levels, based on monostatic data recorded at Edinburgh, could be biased towards lower wind speeds, particularly during the day. The data may therefore be only of value for providing a lower bound on wind speed during such periods.

While the performance of the bistatic system was shown to be superior at a height of 160 m, insufficient data have been obtained for a quantitative assessment of the relative capabilities of monostatic and bistatic techniques for wind measurements at other heights. Furthermore, apart from some initial balloon tracking experiments, the accuracy of these acoustic techniques has not been thoroughly checked.

5.5 Additional problems encountered in measurements

5.5.1 Antenna sidelobes

While the strongest signals measured using the bistatic configuration shown in figure 2(c) generally originate from the region defined as the common scattering volume, the signal-to-noise ratio of scattered returns received via sidelobes above and below this region is frequently adequate to enable a comparison between monostatic and bistatic wind data to be made over an extended height interval. In general, such a comparison indicates that these data are in reasonable agreement in the vicinity of the common scattering volume, at a height of about 160 m (figure 13 shows a series of wind speed profiles recorded at Edinburgh during the period 2106 to 2250 C.S.T. on 5 February, 1976). However, the bistatic results are generally found to underestimate and overestimate the monostatic data below and above the common volume respectively. A possible source of error in bistatic wind data resulting from the use of scattered signals received via antenna sidelobes is shown in figure 14. The contours show the relative intensity in dB of scattered bistatic signals collected by the receiving antenna (2 m and 0.6 m diameter in figures 14(a) and (b) respectively) from unit scattering volumes distributed over a vertical plane containing the transmitting and receiving antennas. An idealized sidelobe distribution with well defined nulls is assumed, which generally does not occur in practice. Ellipses of constant propagation time, in seconds, between transmitting and receiving antennas are also shown as near-horizontal dotted lines.

The contours in figure 14(a) show a well defined common scattering volume formed by the intersection of the main 'beams' of the transmitting and receiving antennas at a height of about 160 m (propagation time about one second). The strong returns from the common volume would be expected to dominate the weaker returns from other regions along the one-second ellipse and therefore, to give reasonably accurate Doppler information. Below the common volume, however, scattered returns could originate from a number of regions as shown, for example, along the 0.5 s ellipse. As the scattered signals from each region may have different Doppler frequency shifts, wind information computed using sidelobe radiation from below (and above) the common volume must be considered unreliable. A complex scattering pattern is also shown for the 0.6 m diameter receiving antenna in figure 14(b), necessitating the maximum possible reduction in antenna sidelobes if a wide beamwidth receiving antenna is to be employed.

Because of the errors in bistatic wind measurements introduced by antenna 'sidelobes' a desirable bistatic system should therefore involve either:

(a) a highly directional, scanned receiving 'beam' with low sidelobes to maintain the maximum signal-to-noise ratio as the transmitted pulse propagates upward, or

(b) several receiving antennas spaced or directed to cover an extended height interval.

Alternatively, when the vertically pointing antenna at the centre is employed to receive scattered acoustic energy, a 'stepped beam' transmitting antenna, or multiple transmitting antennas, would maintain maximum signal-to-noise ratios and minimize sidelobe problems.

5.5.2 Spectral studies

Two problems associated with the antenna systems and the cables from the antennas to the fixed van at Edinburgh, which were investigated using spectral analysis techniques, are illustrated in figure 15. In the 'out-of-lock' condition, with ambient noise collected by inclined, unscreened acoustic antennas applied to the inputs, the Doppler tracking loops were found to have a large negative voltage offset, corresponding to an indicated Doppler frequency shift of about -50 Hz from the 2500 Hz carrier. Without a reliable form of 'lock indicator' such an offset would be averaged with 'good' data, resulting in large errors in computed wind information. The output of one such tracking loop, converted to an equivalent input frequency in Hertz, is plotted as a function of time in seconds in figure 15(c). The frequency offset and the large, random excursions which occur when the loop is out of lock, are illustrated.

The reason for the offset was readily determined from a spectrum of the input to the tracking loop, shown in figure 15(a). The rapid decrease in spectral intensity shown between 2300 to 2400 Hz and 2600 to 2700 Hz is due to the response of the bandpass filters preceding the tracking loop, which are employed to reduce unwanted noise. The drop in intensity between 2400 and 2600 Hz (which should be independent of frequency for white noise) indicated that the sidelobe distribution of the inclined, unscreened acoustic antennas was biased towards the collection of low frequency (2400 to 2500 Hz) ambient noise, to which the tracking loops were responding. The problem was minimized by fitting acoustic screens to the antennas. This effectively reduced both the overall ambient noise level, and the frequency dependence of the antenna sidelobes for the collection of low frequency noise.

The reduction in ambient noise levels resulting from the use of acoustic screens produced a secondary problem, particularly under quiet conditions, when the Doppler tracking loops were frequently found to be 'in lock' even though scattered signals were absent. This apparently good quality data could have biased the statistics and produced errors in measured wind information. The output of a tracking loop during such a quiet period is plotted as a function of time in seconds in figure 15(d). The relatively small fluctuations (compared to figure 15(c)) and the consistent offset in the vicinity of about 2450 Hz indicate that the loop was 'in lock' over most of the period. The frequency spectrum of the input to the tracking loop, shown in figure 15(b), indicated that the loop was tracking harmonics of the 50 Hz mains frequency (2450 to 2550 Hz) picked up on the cables between the antennas and the fixed van. While this problem was partially overcome by moving the cables and with improved earthing, the results highlight the need for preamplifiers near the receiving antennas when long cables are involved, to minimize the effect of mains harmonics.

6. THE MOBILE ACOUSTIC WIND-SENSING FACILITY

The mobile acoustic wind-sensing facility, described briefly below, was designed to investigate temporal and spatial variations of wind structure over an airfield, as required by sub-study (iii) outlined in Section 2. This sub-study was considered necessary, when formulating the task, to investigate and assemble statistical data on the spatial extent and variability of wind shear phenomena, and to compensate for the limited operating range of the fixed facility at Edinburgh. For example, a single acoustic wind-sensing system can only provide wind information from a localized region above the sensors. If appreciable variations in wind shear occur over the extent of an airfield, more than one acoustic system would have to be deployed, with a substantial increase in complexity and cost. Alternatively, other remote sensing systems capable of long range operation with perhaps more flexibility in spatial coverage, might be considered more desirable as a wind sensor.

A simplified block diagram of the mobile acoustic wind-sensing facility is shown in figure 16. Four independent acoustic antennas and associated field electronics sub-system (see figure 6) are connected to a mobile van via cables, approximately one kilometre in length. The antennas can therefore be closely spaced for localized wind measurements or separated by distances of up to two kilometres for studies of horizontal variations in the mean wind field. The transmission sequence is initiated by sending an 8.33 kHz burst from a timing and sequencing unit along the respective cables from the van to the battery-operated field sub-system. These contain 100 W transmitters (audio power amplifiers), relays and frequency dividing and pulse-shaping circuitry. In the receive mode, received signals are amplified and filtered within the field sub-system and then transmitted back to the van via the cables. A d.c. current is also passed along the cables from the van to charge the batteries.

Doppler tracking loops and logarithmic amplifiers in the van produce wind and 'microstructure' information which is sampled by a 16 channel analogue multiplexer, averaged in a microcomputer and punched on paper tape. A height versus time record of atmospheric 'microstructure' observed by the four antenna systems can be obtained by transmitting sequentially and multiplexing the four channels on to a single fascimile recorder. Range gates and analogue integrators provide fixed level data for recording on an analogue pen recorder. Two of the four antenna systems are currently operating satisfactorily at Edinburgh, with a horizontal separation in excess of one kilometre, and performance and wind data will be considered in a subsequent report.

7. THE PROGRAMME OF RESEARCH DURING THE REMAINDER OF THE TASK

7.1 General

It is anticipated that due to other commitments, manpower resources at W.R.E. devoted to the wind shear task will be progressively reduced during 1977.

The results obtained to date have demonstrated that the performnace of the existing Edinburgh facility falls short of the range requirements for an effective wind shear sensor at an airfield. This report has already indicated areas where perhaps a significant improvement in this performance could be achieved. However the required modifications to the facility are likely to be expensive (i.e. in-ground screening bunkers for antennas or multiple transmitting antennas), and would tend to duplicate research programmes overseas. The programme of research at W.R.E. during the remainder of the task (described briefly below) will therefore be restricted to investigations which can be conducted in a reasonable time, with a minimum of effort, using existing facilities.

7.2 The collection of statistical data

The centre, north and east acoustic antennas shown in figure 1 have been surrounded by wooden screens lined with glass wool to reduce, as far as possible, the received levels of ambient noise created by aircraft, wind, traffic, etc. These screened antenna systems will provide monostatic data, with bistatic data collected using the centre antenna for reception, for the remainder of the task. Monostatic data on horizontal variations in the wind field at Edinburgh over a separation of about one kilometre will also be collected using the mobile acoustic wind-sensing equipment. These wind and performance data will be presented in the final report. It is also hoped to be able to provide some quantative assessment of the relative capabilities of monostatic and bistatic systems for wind measurement.

7.3 Investigation of advanced signal-processing techniques

One of the major disadvantages of acoustic wind-sensing systems for airport applications is the possible degradation in performance with the high levels of ambient noise created by aircraft and strong winds. Observations based on the relatively simple acoustic system employed at Edinburgh indicate that a reduction of several orders of magnitude in collected ambient noise power, or a corresponding improvement in received signal level, would be necessary for reliable operation during such periods. Improvements are therefore necessary in the design of antennas and acoustic screens (to reduce the collection of ambient noise power), in high powered transducers (to increase the radiated acoustic power) and in signal processing techniques (to reduce the effective noise bandwidth). For example, an improvement in performance could possibly be achieved using some of the advanced signal-processing techniques being developed for electromagnetic radars. Experiments have therefore been initiated to investigate the feasibility of improving the performance of the system employed at Edinburgh using 'coded' pulse transmissions and digital signal-processing techniques.

7.4 Control tower warning and display system

The development of hardware and software for a warning and display system suitable for installation in a control tower, and satisfying the requirements of air-traffic control personnel, was considered a major objective when the task was formulated. Considerable effort will be required to interface the wind sensing system with such a remote display and to develop software for a dedicated minicomputer. The justification for development of a suitable display during the remainder of the task will depend upon factors such as the results of a survey presently being conducted by A.R.L., available effort and the task priority. As experimental display systems are currently in operation in the United States, further local effort on this aspect would be worthwhile only if the Australian requirement differed significantly from overseas systems, to avoid duplicating overseas work.

7.5 Investigation of other remote wind-sensing techniques

A pulsed neodymium-YAG laser and photographic recording system has recently been developed at W.R.E. Data on the relative performance of aerosols as optical scatterers for wind measurement, compared with acoustic sounding, will be available during 1977.

It is not expected that a laser system suitable for wind measurement will be developed at W.R.E. in the near future, because of funding limitations on equipment procurement. However, a literature search is being made on current overseas research in laser sensors, and the results will be published as a separate report.

8. SUMMARY AND CONCLUSIONS

An essential requirement for any remote wind-sensing system is the ability to operate satisfactorily under all conditions likely to be associated with wind shear phenomena, including strong surface winds and turbulence, gusts, etc. The data on the performance of monostatic and bistatic configurations presented in Section 5 indicate that the relatively simple, low powered systems with analogue Doppler processing, as employed at Edinburgh, are not suitable for use as remote sensors (in their present form) at airfields. In general, aircraft on the nearby runway, strong surface winds, heavy rain, etc., are found to render the Edinburgh system inoperable, resulting in possible errors in computed wind statistics, particularly during the day.

The relatively poor performance of the Edinburgh facility should not be taken to indicate, however, that acoustic remote wind-sensing systems have no future for airport applications. The development of such systems and suitable displays is continuing overseas, particularly in the United States, where comprehensive facilities exist for evaluating the performance and applications of both acoustic and electromagnetic remote sensing techniques. Effort devoted to any major modification of the Edinburgh facility would merely tend to duplicate existing programmes of research overseas.

Future acoustic wind-sensing research will be concentrated on the aspects which will be most cost effective in terms of the effort available. The investigation of advanced signal processing techniques is seen as the most important area for further study, combined with the collection of additional statistical data at Edinburgh.

The development of a warning and display system for wind shear will depend partly on the results obtained from a survey of pilots and air-traffic controllers, and will require strong justification for the expenditure of further effort in this direction at W.R.E.

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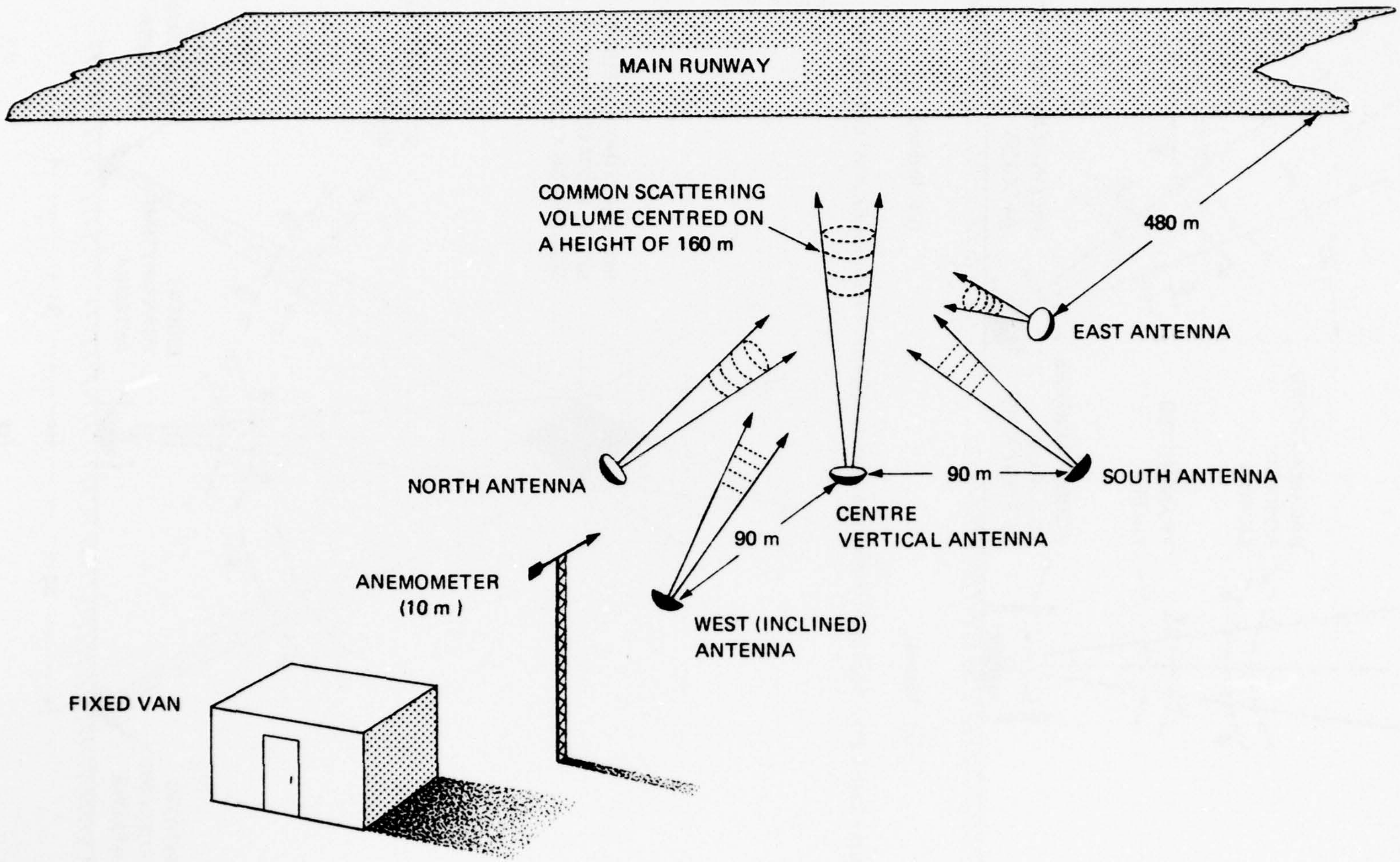

Figure 1. Configuration employed for the experimental acoustic wind-sensing facility at Edinburgh airfield.

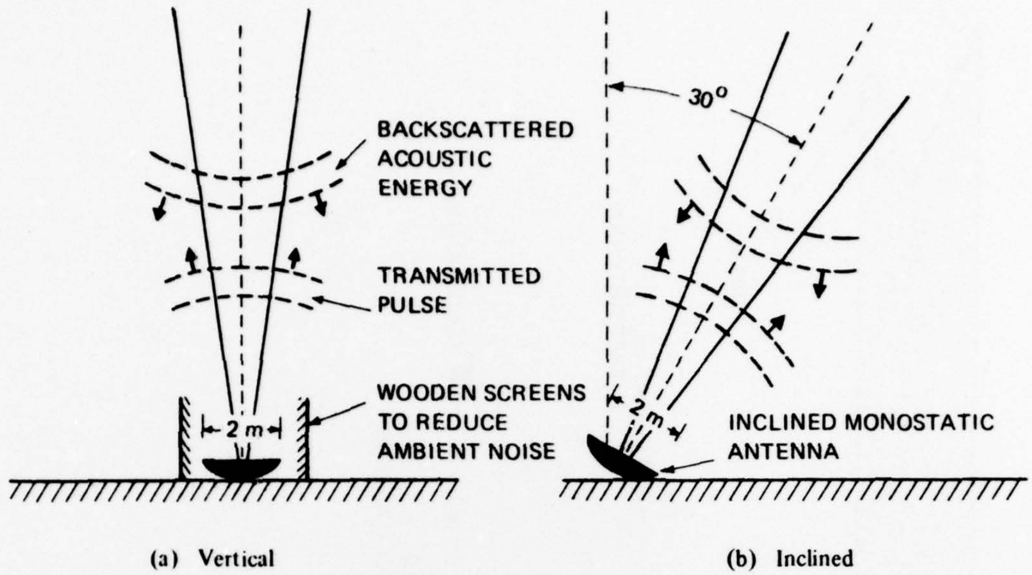

Figure 2 (a) & (b). Acoustic antenna configurations employed for monostatic wind measurements.

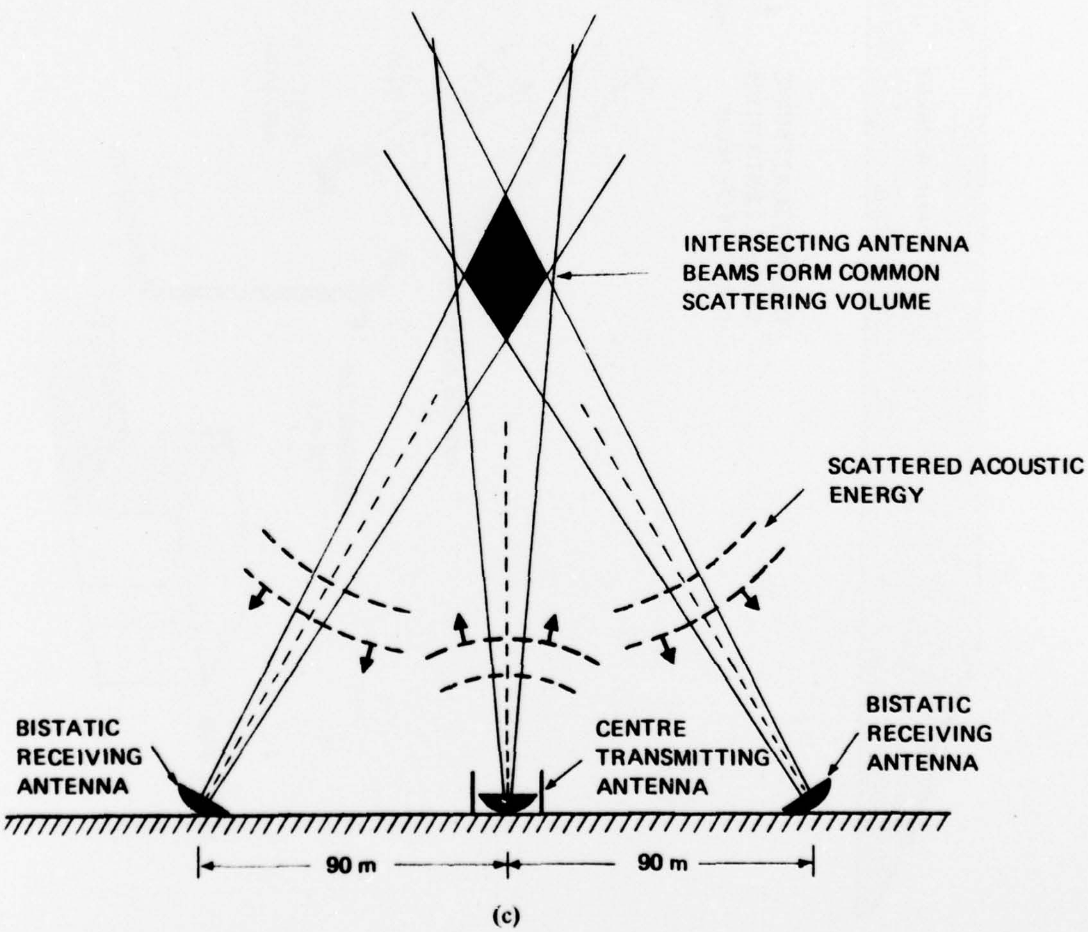

Figure 2(c). Acoustic antenna configuration employed for bistatic wind measurements

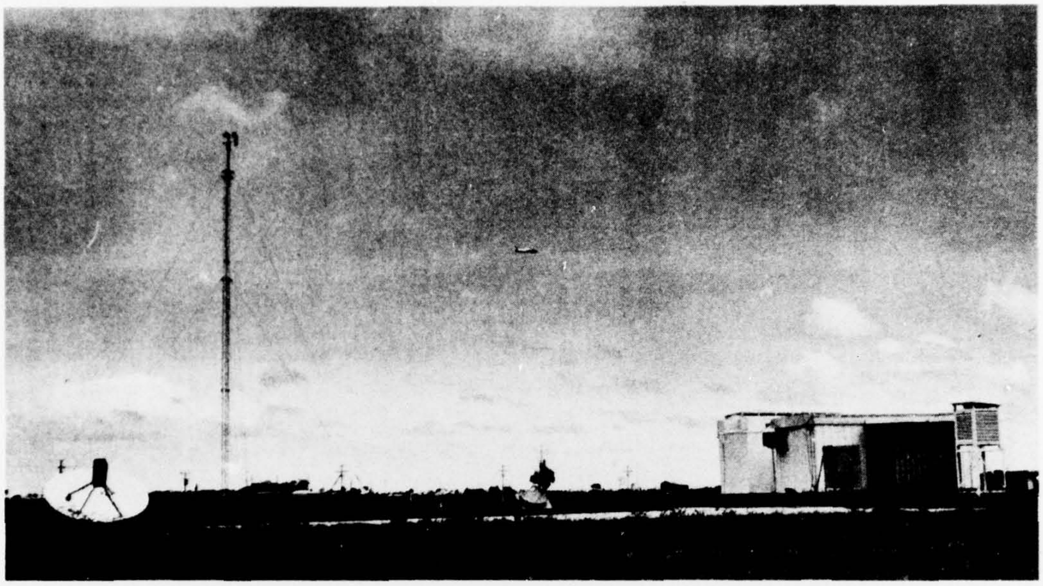

Figure 3. Photograph showing the fixed van, meteorological tower and west acoustic antenna (unscreened, 2 m diameter) at the Edinburgh facility.

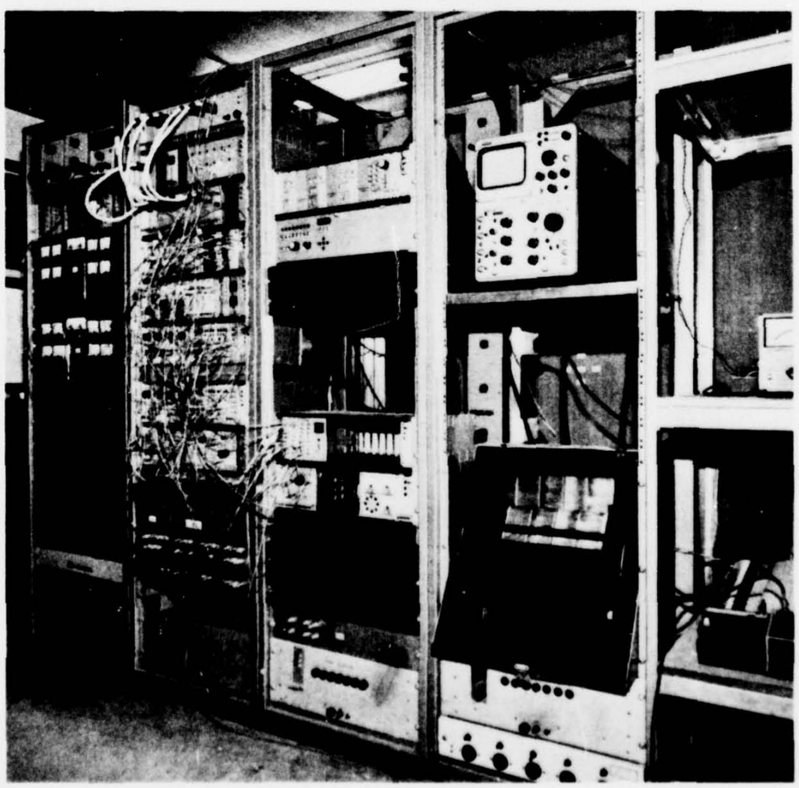

Figure 4. Photograph showing the transmitting, receiving and recording equipment in the fixed van at the Edinburgh facility.

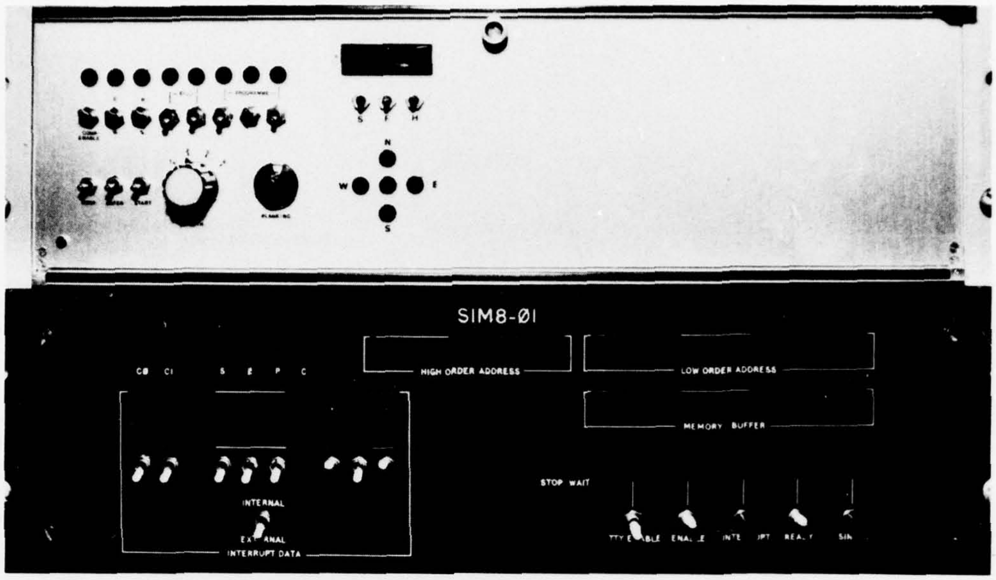

Figure 5. Photograph showing the digital mode-control unit (top) and the micro-computer (Intel 8008 CPU) used to collect, average and record acoustic-sounder wind data at the Edinburgh facility (see Section 4).

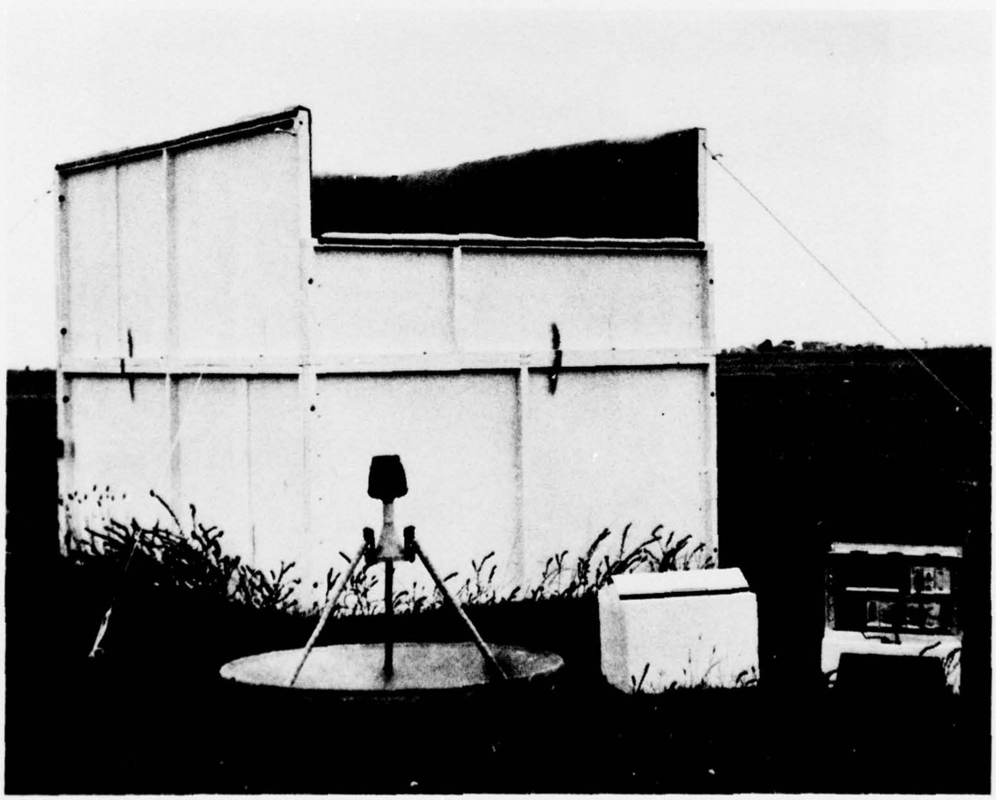

Figure 6. Photograph showing an acoustic antenna (1.2 m diameter), field-electronics subsystem and acoustic screen developed for the mobile acoustic wind-sensing facility, described in Section 6.

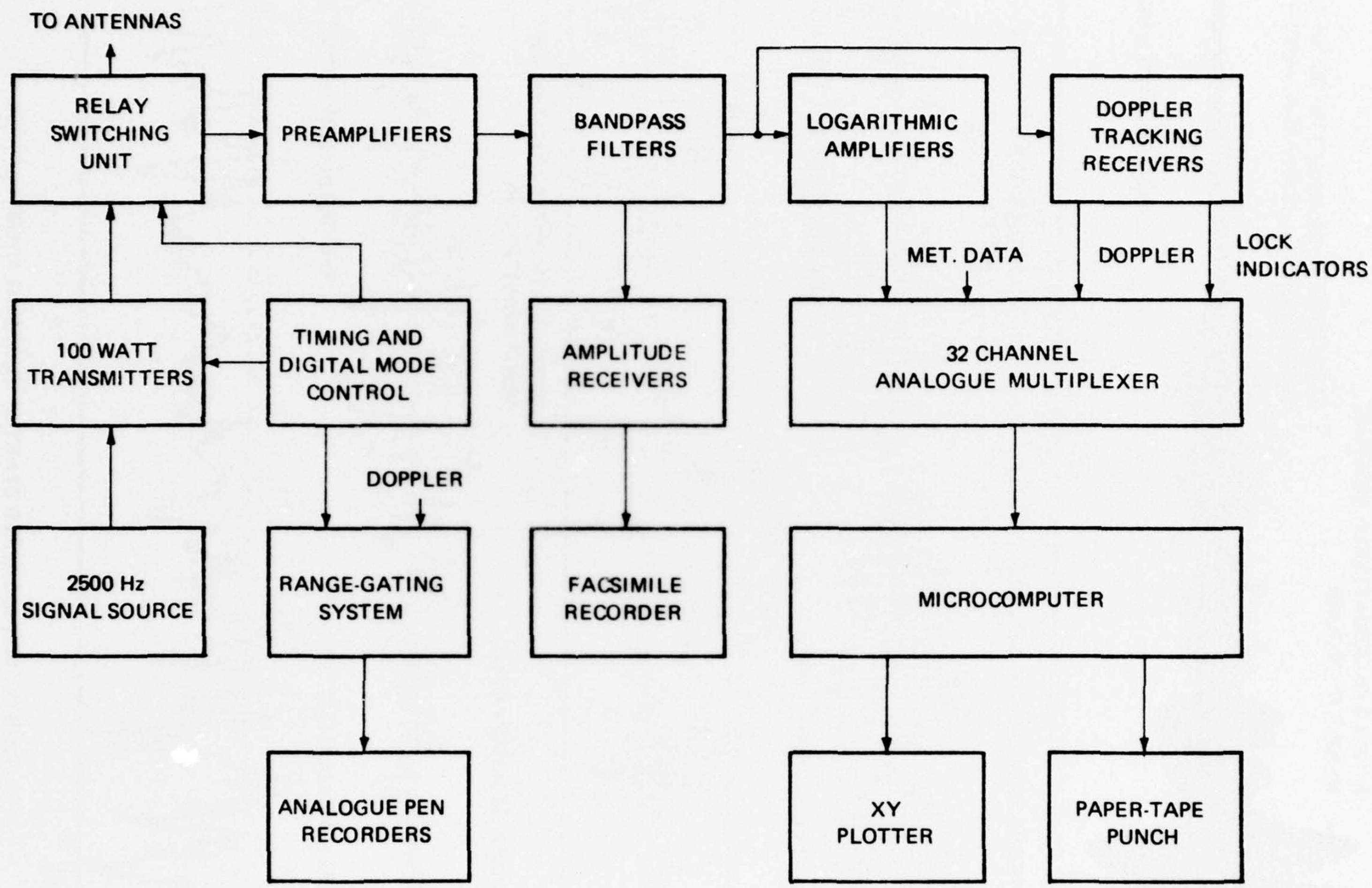

Figure 7. Simplified block diagram of the transmitting, receiving and recording system at the Edinburgh site.

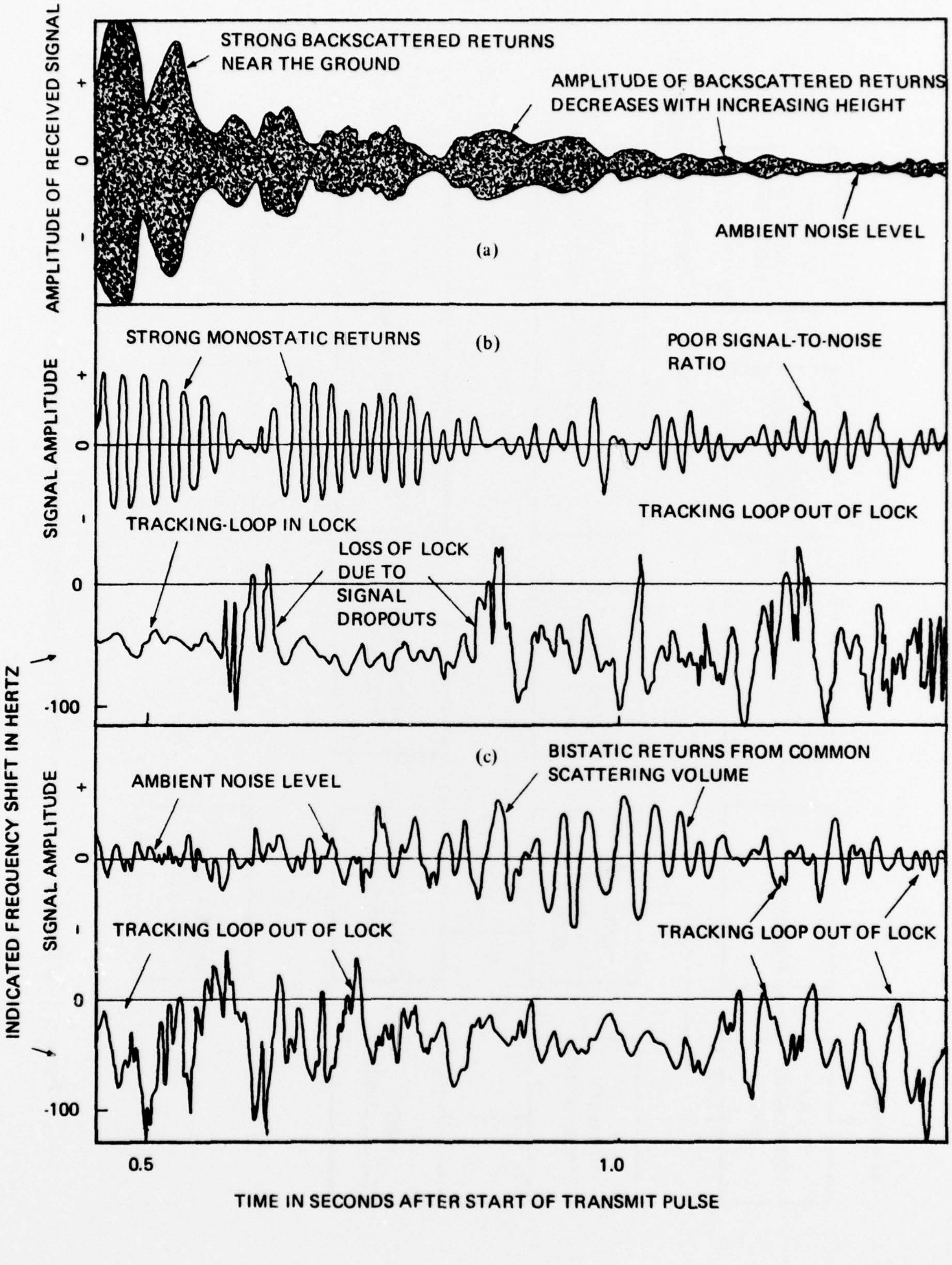

Figure 8. Examples of the signals received using monostatic and bistatic configurations, and the outputs of the Doppler tracking loops.

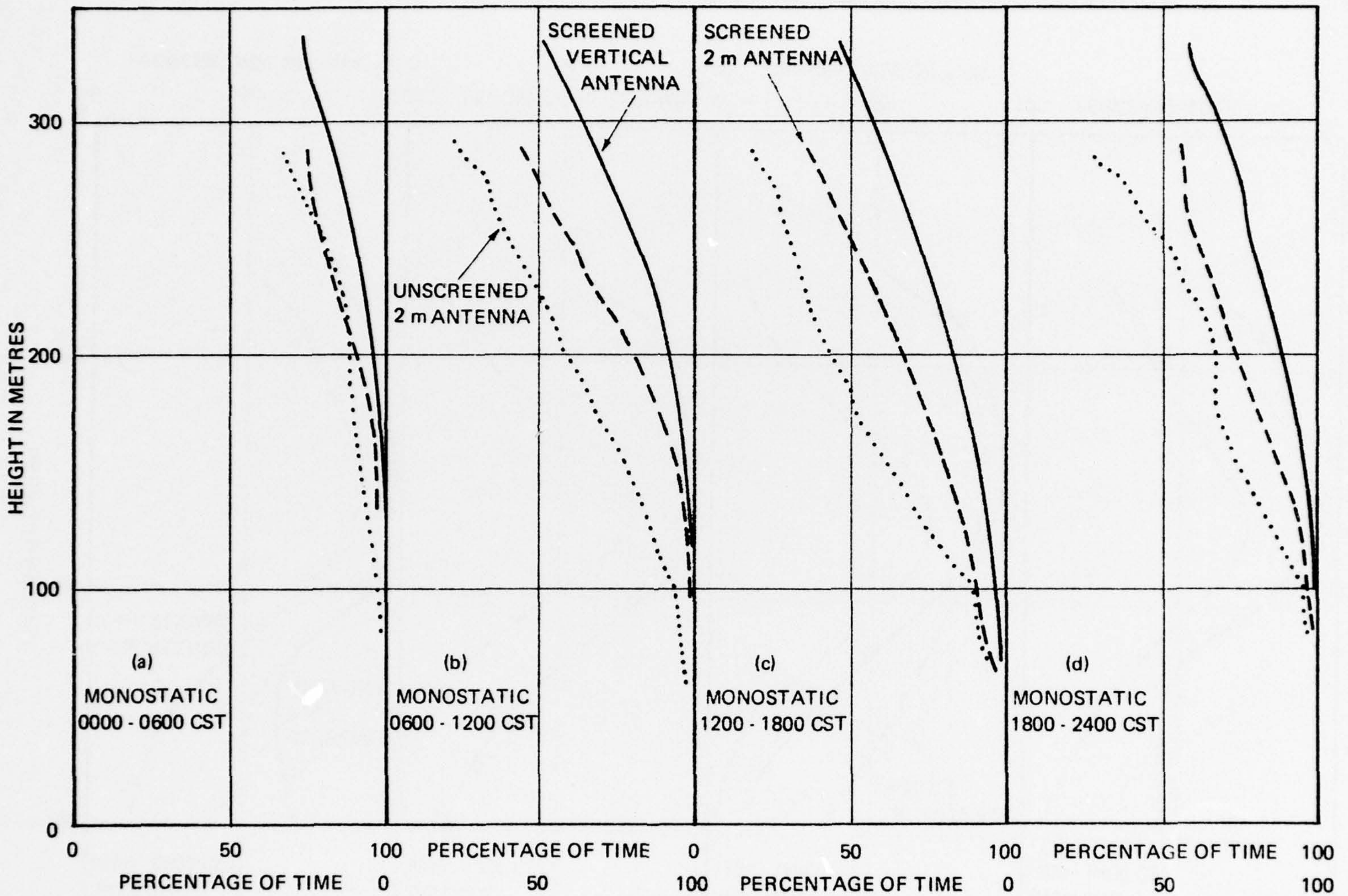

Figure 9. Percentage of time that useful monostatic wind data was recorded at the Edinburgh facility (over a period of about one month), plotted as a function of height in metres for four, six-hour periods.

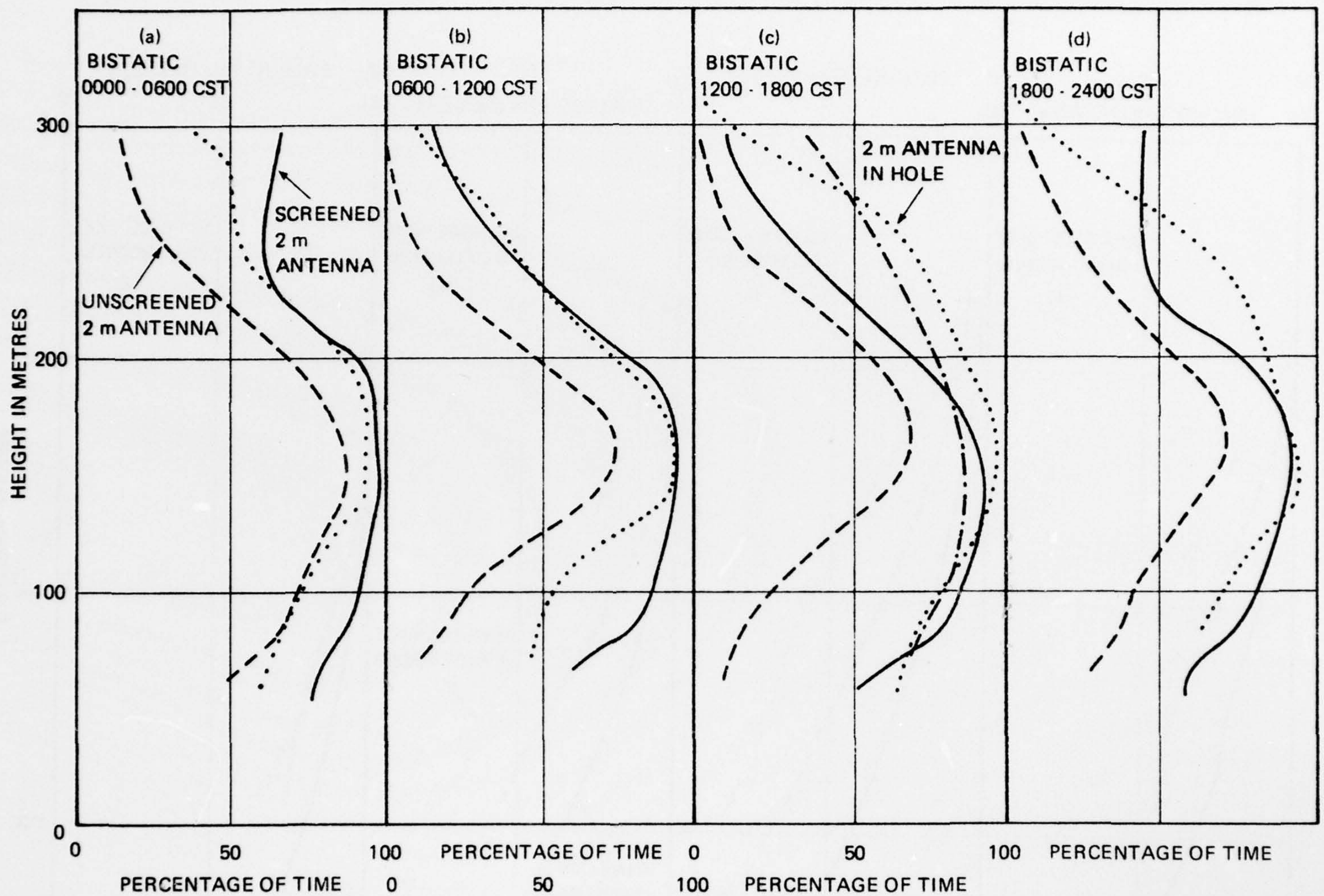

Figure 10. Percentage of time that useful bistatic wind data was recorded at the Edinburgh facility (over a period of about one month), plotted as a function of height in metres for four, six-hour periods.

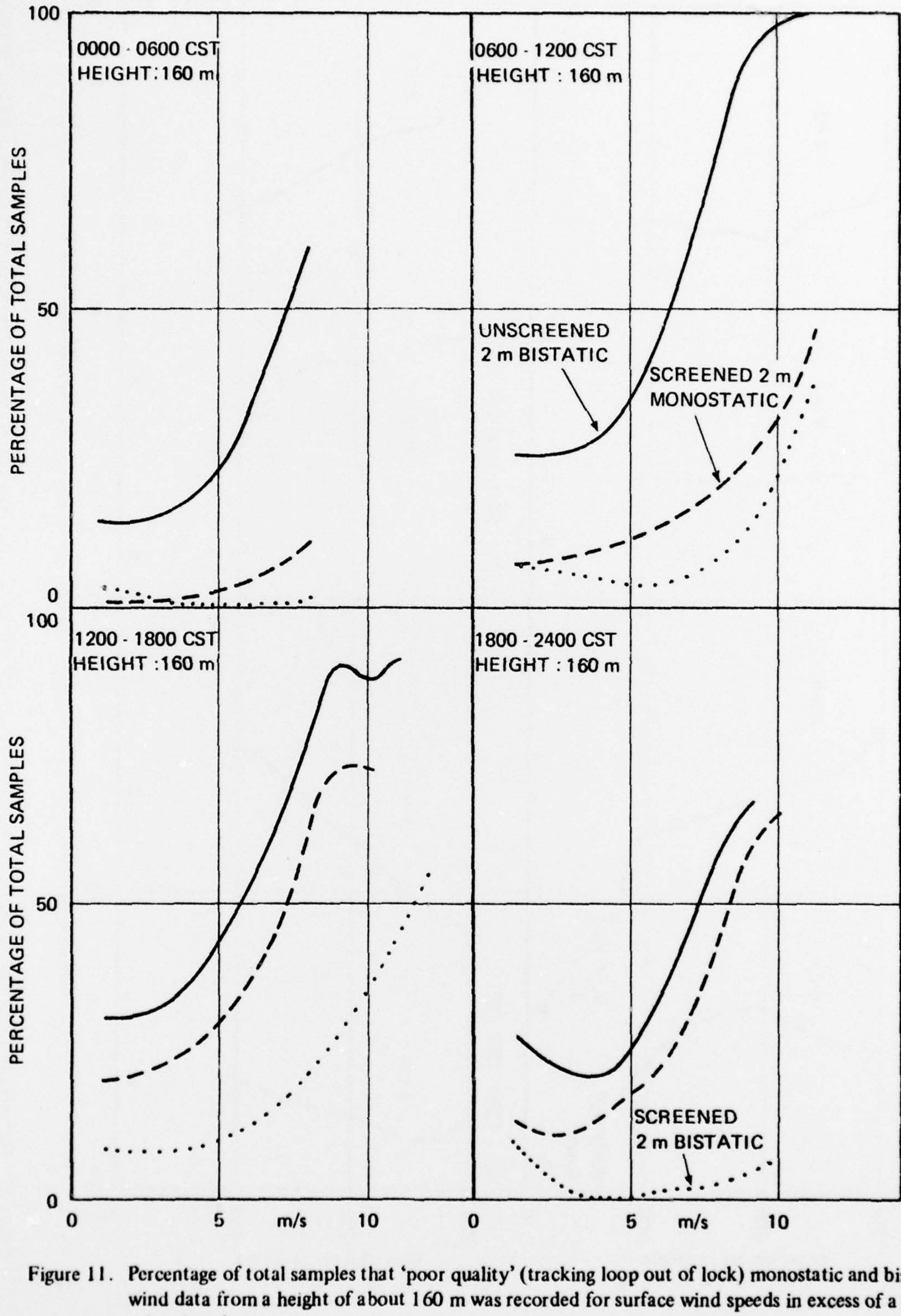

Figure 11. Percentage of total samples that 'poor quality' (tracking loop out of lock) monostatic and bistatic wind data from a height of about 160 m was recorded for surface wind speeds in excess of a given value, in m/s.

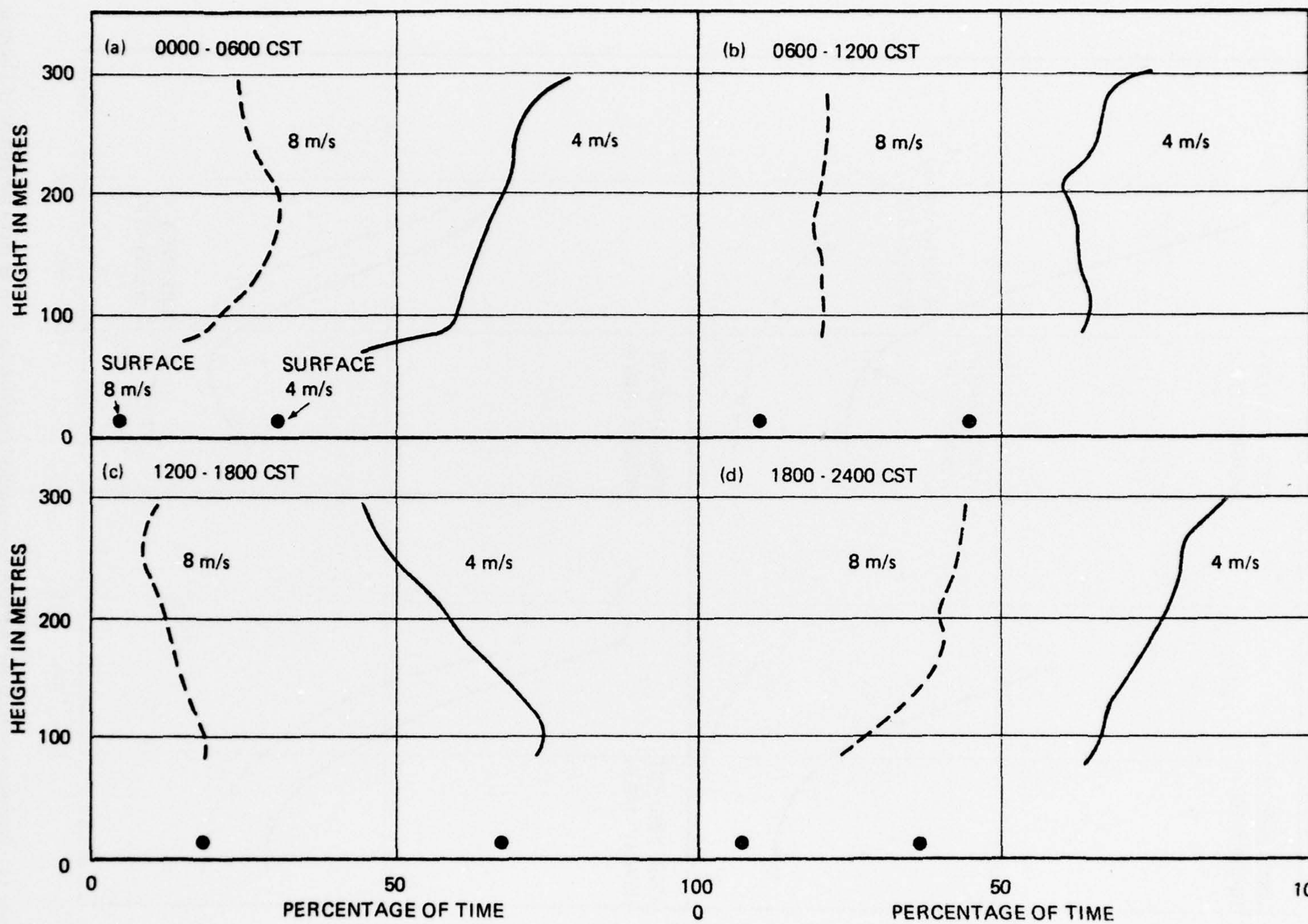

Figure 12. Percentage of time that the measured wind speed exceeded 4 m/s and 8 m/s respectively, plotted as a function of height in metres for four, six-hour intervals.

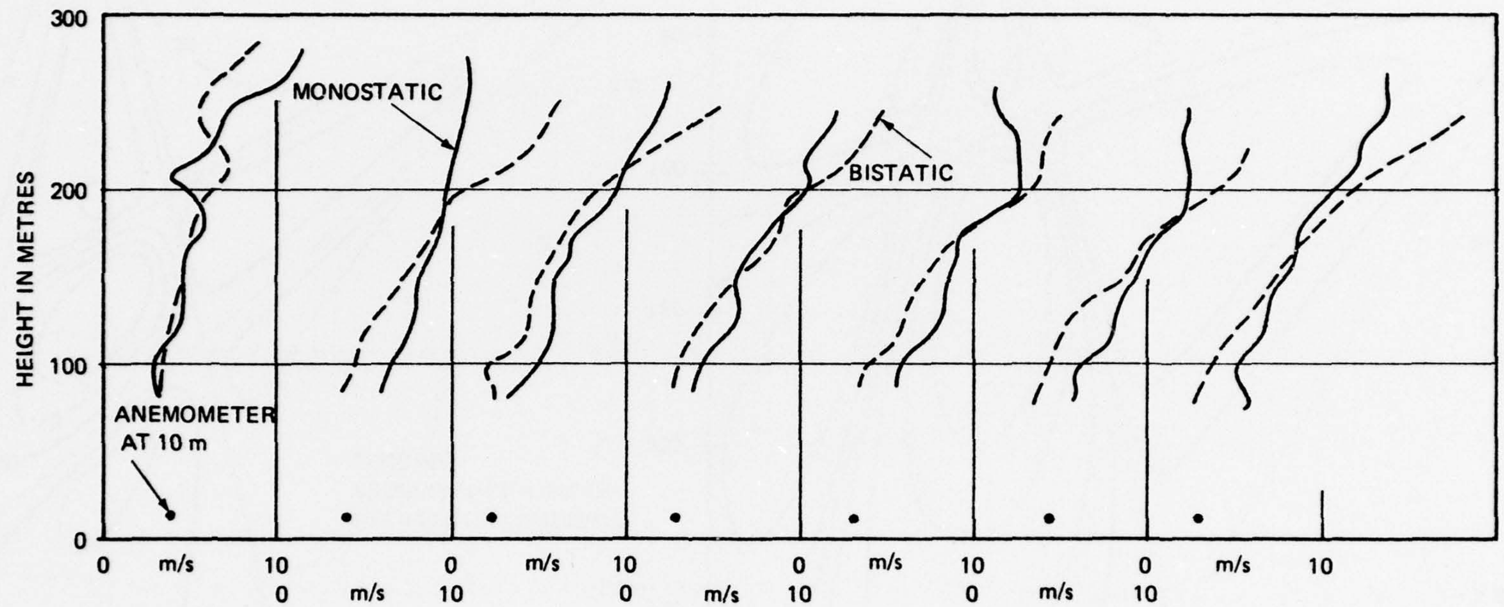

Figure 13. Monostatic (solid lines) and bistatic (dotted lines) wind speed profiles recorded at Edinburgh during the period 2106 *to* 2250 C.S.T. on February 5, 1976.

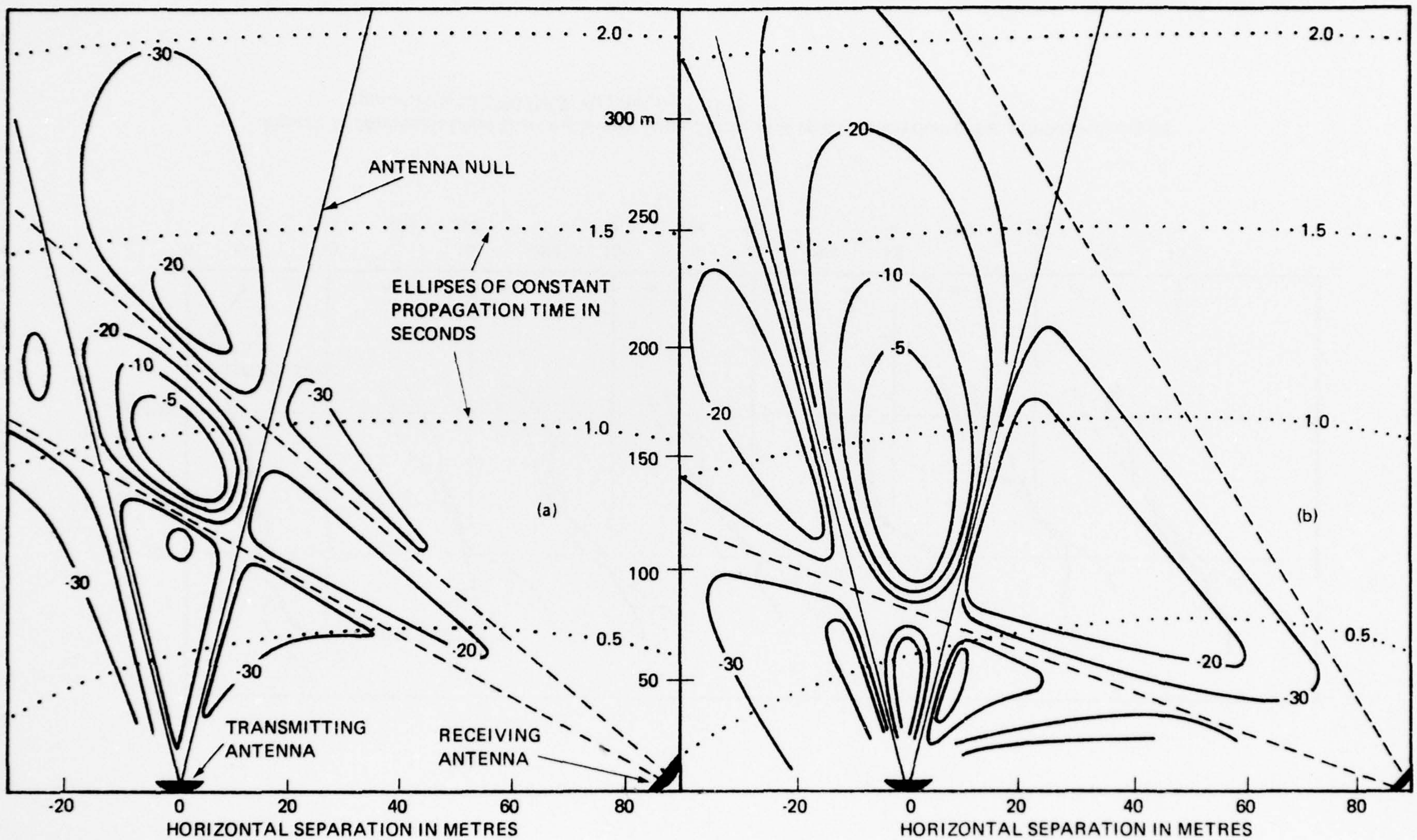

Figure 14. Computed contours of constant scattering intensity per unit volume in a vertical plane containing both antennas
(a) 2 m transmitting and receiving antennas (b) 2 m transmitting and 0.6 m receiving antennas.

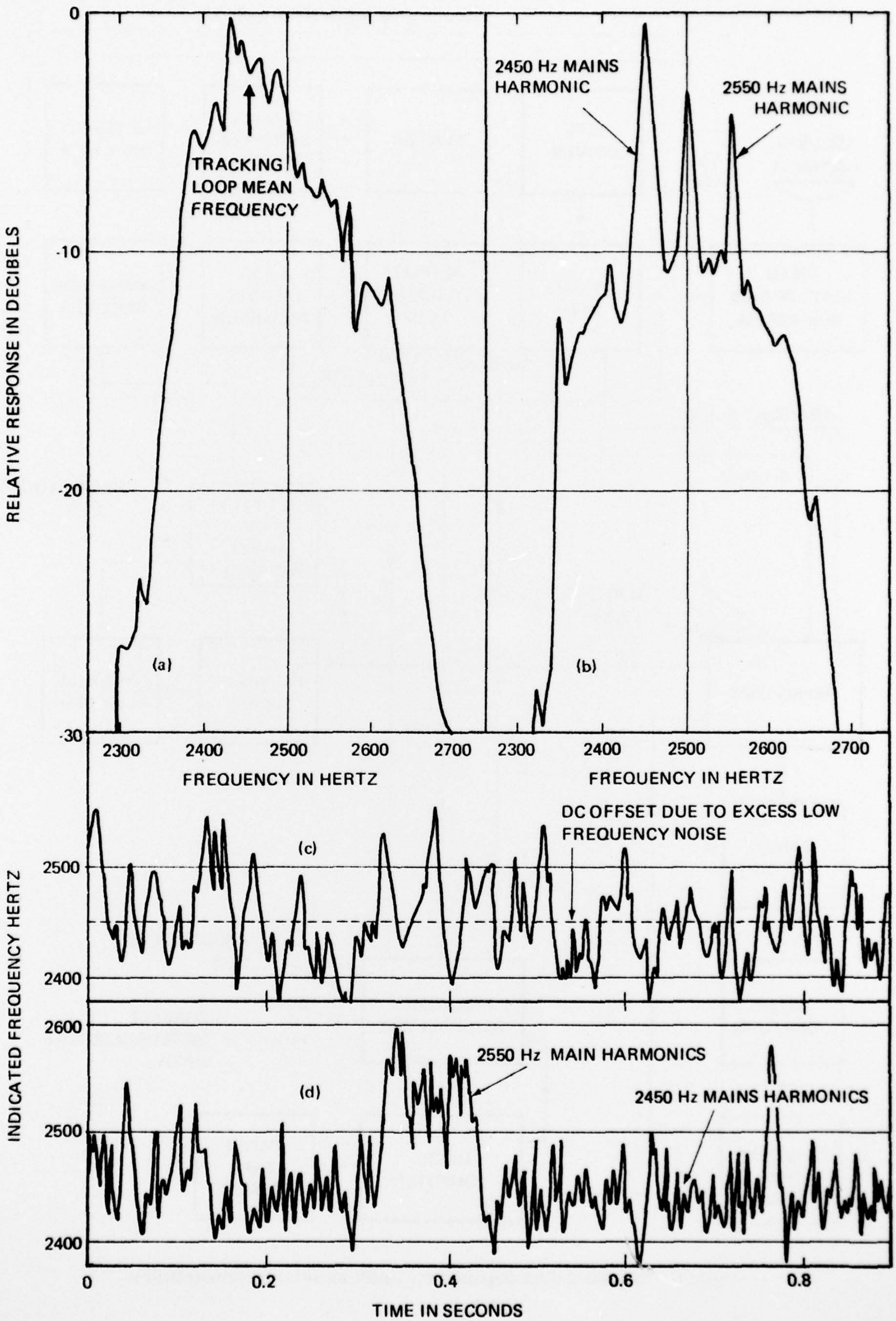

Figure 15. Doppler tracking loop outputs and associated frequency spectra illustrating problems encountered with the acoustic antennas and cables.

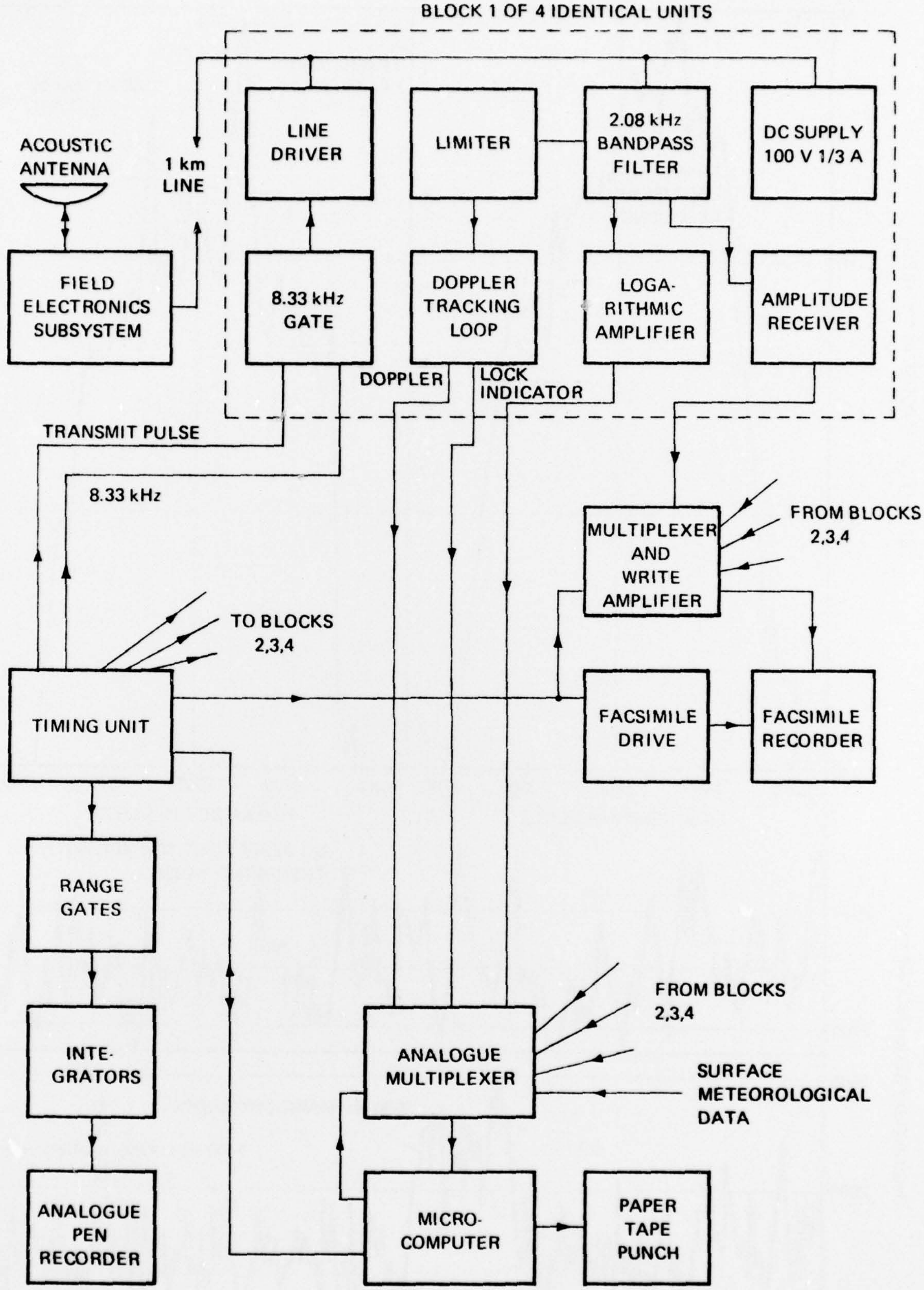

Figure 16. Simplified block diagram of the mobile acoustic wind-sensing facility.

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